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THE INPAD PROJECT: AN INVESTIGATION INTO THE AXIAL CAPACITY OF PILES IN SAND

Introduction

To determine a pile's axial capacity, NEN 9997-1 correlates the base resistance q_b and shaft resistance q_s to the cone tip resistance q_c from a cone penetration test (CPT):

$$q_b = \alpha_p q_{c,avg} \leq q_{b,lim} \quad (1)$$

$$q_s = \alpha_s q_c \leq q_{s,lim} \quad (2)$$

where $q_{c,avg}$ accounts for the variation in cone resistances around the pile base using the "Koppejan 4D/8D" averaging method, $q_{b,lim}$ and $q_{s,lim}$ are limiting resistances, and α_p and α_s are pile class factors determined by the installation method and soil type.

In 2017, a review of static load tests (Stoevelaar et al., 2014) led to a reduction in α_p by 30% for all pile types. However, this change was met with resistance from the industry: partly because of the rarity of pile failures, but also because of the greater installation difficulty and higher costs associated with larger piles. The review also cited the lack of instrumented pile tests—limiting the ability to separate the base shaft and capacities from the total capacity.

Site	*Piles*	*Diameter (mm)*	*Length (m)*	*Max. test load (MN)*	*Notes*
Amaliahaven, Maasvlakte 2	4 x screw injection 4 x driven cast-in-situ 3 x driven closed-ended	610/850 380/480 400x400	32–37 33 31	18–23 7–9 8–9	Comparison of installation methods at the same site. Piles installed in very dense sand with q_c values up to 80 MPa. Published in Duffy et al. (2024).
Deltares, Delft	3 x driven closed-ended	350x350	21	1–2	Investigation of residual load development and aging in soft clay overlying dense sand. Partially published in Duffy et al. (2022).
FloodProof Holland, Delft	6 x screw injection	380/470	20	2–3	Comparison of Fundex and Tubex piles installed in soft clay overlying dense sand ($q_c \approx 12$ MPa). Published in Duffy et al. (2024).
Lemmer	15 x screw injection	380/470	10	0.9–1.3	Tests investigating the influence of different installation parameters on the piles' tensile capacities (Admiraal et al., 2022).
Witte Zeeweg, Maasvlakte 2	4 x driven open-ended piles	1200	32	12–23	Assessment of open-ended piles installed by vibration in the upper layers and hammering in the lower, denser layers.

Table 1 – Test sites in the InPAD project. The edge length is presented for the (square) driven closed-ended piles.

To address these issues, the InPAD (Investigation of the Axial Capacity of Piles in Sand) project began in 2019 and ran for five years. Led by TU Delft and Deltares, the project was funded by TKI Deltatechnologie, Port of Rotterdam and Rijkswaterstaat, along with in-kind contributions from Fugro, Gemeente Rotterdam and the NVAF (Nederlandse Vereniging Aannemers Funderingswerken). InPAD focussed on five research questions:

- What is the appropriate averaging method for determining $q_{c,avg}$?
- Are limiting resistances on the base and shaft capacity necessary?
- What are the appropriate pile class factors for the different types of screw displacement piles?
- How should plugging be considered in the design of open-ended piles?
- How does friction fatigue affect the shaft capacity of driven precast and driven cast-in-situ piles?

Ultimately, accurately defining these mechanisms can greatly optimise pile design–reducing the financial and environmental costs of pile production and installation, whilst maintaining a high level of reliability. With this in mind, this article outlines the research methodology in InPAD, and then summarises the findings from each of the five research questions above.

Figure 1 – Testing screw injection piles at Delft with a load test frame and concrete ballast.

Methodology

InPAD followed two parallel research tracks: full-scale field testing and small-scale physical modelling in the laboratory. Small-scale modelling gave insights into the interaction mechanisms which affect a pile's axial response, whilst field testing provided a validation of these mechanisms in conditions similar to industry practice.

FULL-SCALE FIELD TESTS

The field tests explored several common pile types: driven open-ended, driven closed-ended,

SUMMARY

The InPAD project investigated the axial capacity of different pile types in sand, including driven precast piles, screw displacement piles and driven cast-in-situ piles. This was done through several full-scale field tests and small-scale physical models, using state-of-the-art instrumentation to analyse the base and shaft response of each pile. This article shows some of the findings from the project and puts forward recommendations for the NEN 9997-1 pile design method.

driven cast-in-situ (vibropalen) and screw injection piles. Five test sites were established in consultation with the national pile test committee NPR 7201 (Table 1), comprising 39 piles in total.

Four of the test sites, funded by the Port of Rotterdam and Rijkswaterstaat, focussed on piles installed in conditions similar to industry practice. All of these piles were installed down to the Pleistocene sand, known geologically as the Kreftenheye Formation. At Delft, cone resistances of 10–20MPa were recorded in this formation, whereas at the Maasvlakte, cone resistances were 45 MPa on average—although peaks of up to 80 MPa were also recorded. A test frame, like that shown in figure 1, loaded each pile in axial compression whilst fibre optic sensors measured the base and shaft resistances from which α_p and α_s could then be derived. The Lemmer tests (managed by the NVAF) took a different approach, focussing on how different grout injection parameters affected the shaft capacity of screw injection piles.

Furthermore, historical pile test data was compiled from the TU Delft and Deltares archives, as well as from public literature. The databases include:
- Screw displacement piles: 129 piles (75 instrumented). Includes screw injection piles, DPA piles, Olivier piles, Omega piles etc.
- Driven cast-in-situ piles: 51 piles (26 instrumented)
- Driven precast piles: 9 instrumented (Stoevelaar et al., 2014)

SMALL-SCALE PHYSICAL MODELLING

Soil-pile interaction was simulated at the small-scale with two methods: the calibration chamber and the centrifuge (figure 2). A calibration chamber mimics real-life soil conditions by imposing stresses on the boundaries of a soil sample, just like a triaxial test. An instrumented model pile was then installed into this soil sample, both by jacking (just like a CPT) and by impact hammering under different stress regimes. Through these tests, different installation methods could be studied in detail alongside the necessity of limiting resistances. Secondly, the new GeoCentrifuge of Deltares was used for performing CPTs into soil layers with different properties, such as clay overlying sand or sand layers with different densities. Using different cone diameters, the accuracy of averaging methods in determining $q_{c,avg}$ (Equation 1) could then be assessed.

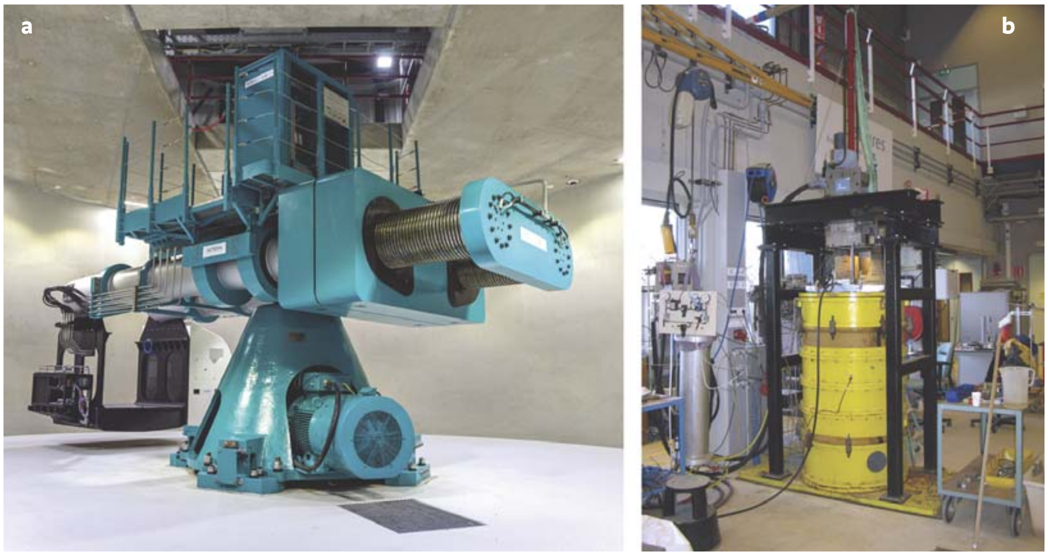

Figure 2 – (a) The GeoCentrifuge at Deltares and (b) the calibration chamber.

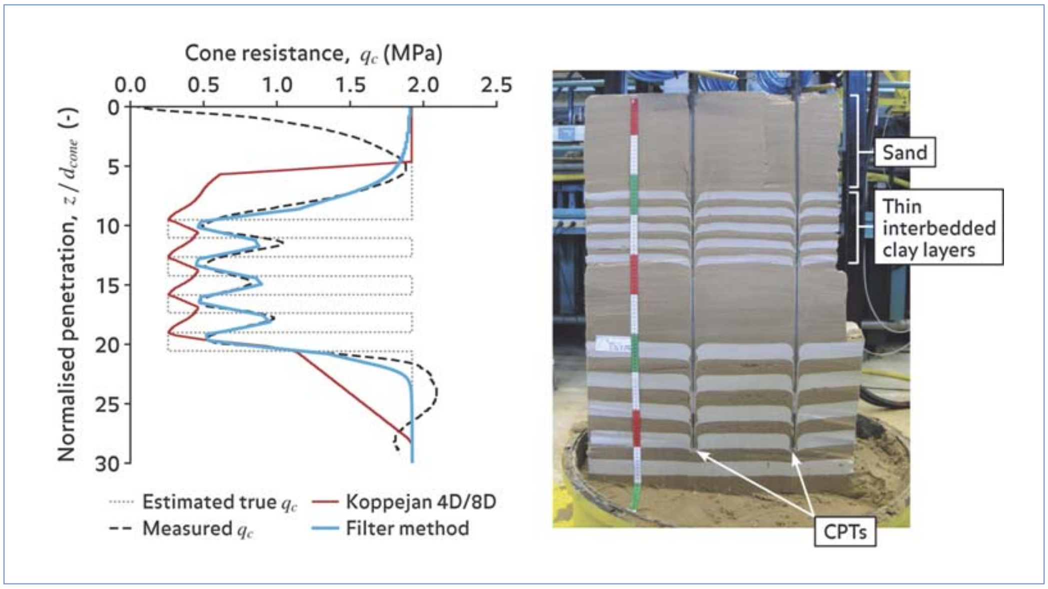

Figure 3 – Calibration chamber tests comparing the predictive performance of averaging methods using an estimated true q_c profile as an input.

Results

AVERAGING METHODS

The distance at which a penetrometer or pile senses a weak layer highly depends on the tip diameter. The same applies to the penetration needed in a stronger layer to develop the full resistance. Therefore, the CPT q_c value should first be adjusted ($q_{c,avg}$ from Equation 1) for the pile diameter before using the pile class factor α_p to estimate the base stress at failure. This is the role of averaging methods.

Different design codes use different averaging methods. For example, NEN 9997-1 specifies the Koppejan 4D/8D method, while Belgium's design code NBN EN 1997-1 ANB adopts the "De Beer method". Recent research (Boulanger and DeJong, 2018) has introduced the "filter method". The filter method applies a sinusoidal filter to all q_c

values within the pile tip's influence zone, accounting for the relative strengths of the different soil layers and their distance from the pile tip. On average, the filter method yielded $q_{c,avg}$ values 20% higher than the Koppejan 4D/8D method (Lehane et al. 2020), although this varied from case-to-case depending on the soil layering and proximity to weaker layers.

During the InPAD project, de Boorder (2019) compared different averaging methods to CPTs in interlayered soil deposits in a calibration chamber (de Lange, 2018), as well as to measurements from the precast pile database. The research found that the filter method accurately described the measured cone resistances in layered soils, whereas the 4D/8D method systematically underestimated the penetration resistance near layer boundaries (figure 3). Hersbach (2024) also analysed press-in piling data from seven sites across the Netherlands. Again, the filter method could more accurately predict the installation response compared to other averaging methods.

Averaging methods also affect how α_p is interpreted from a pile load test. The records from the screw displacement pile database (figure 4) show how penetration into the load-bearing sand layer affects the derived α_p. When comparing the three methods, the filter method demonstrates the lowest coefficient of variation (COV) in α_p, as well exhibiting the most consistent α_p factors across all embedment ratios.

LIMITING RESISTANCES

Equation 1 and Equation 2 show that NEN 9997-1 limits the shaft and base resistances for design: $q_{b,lim}$ is set to 15 MPa and $q_{s,lim}$ is obtained by limiting the q_c profile to 12–15 MPa (depending on soil layering). These limitations were brought in as a response to the unknown: prior to the load tests at Amaliahaven, very little instrumented piles were brought to failure in very dense sand. Using two different types of fibre optic sensors, the Amaliahaven tests gave detailed measurements of the base and shaft resistances in the very dense Pleistocene sand, where the average cone resistance was around 45 MPa. Under static loading, the driven closed-ended piles reached base resistances of 30 MPa, two times higher than the current limiting resistance.

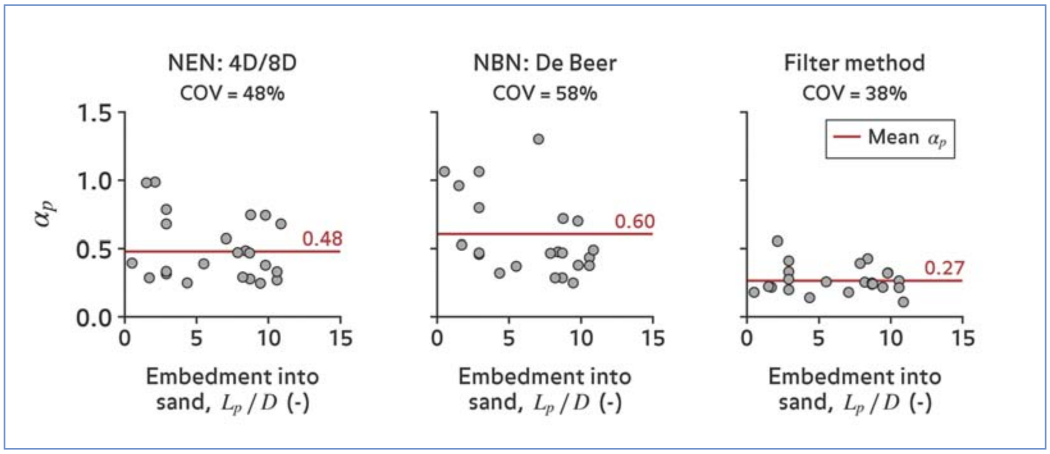

Figure 4 – α_p values from the screw displacement pile database.

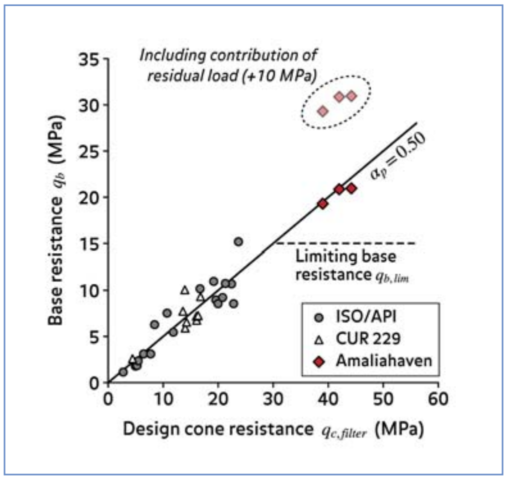

Figure 5 – Measured base resistances at Amaliahaven compared to pile test databases on driven closed-ended piles.

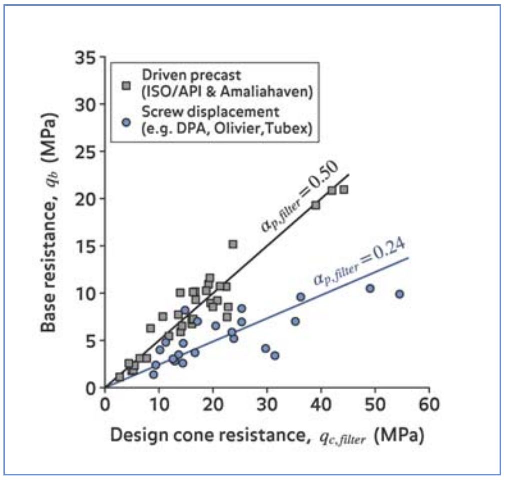

Figure 6 – Measured base capacities from the screw displacement and driven closed-ended pile test databases.

Uniquely, residual stresses were also measured at Amaliahaven. Residual stresses describe the stress state after pile driving, where elastic rebound of the pile and stresses underneath the pile base mobilise friction between the pile shaft and the soil. These measurements are not often performed before load testing, as was the case with many previous load tests. Figure 5 therefore compares the Amaliahaven piles to the database records by excluding the residual base stress of 10 MPa measured at the start of the Amaliahaven tests. Evidently, an $\alpha_{p,filter}$ of 0.50 aligns well with all of the results. In short, recognising the influence of residual stresses is essential for accurately interpreting a pile test, as well as ensuring a robust and reliable CPT-based pile design.

These results were also validated by laboratory tests on jacked and driven piles. In dense, normally to slightly over-consolidated sand samples, a constant α_p was found for base resistances up to 25 MPa. Compared to the driven piles, higher α_p values and a more severe degree of sand crushing was observed for jacked piles.

Similar findings were made for the shaft resistance. For instance, the screw injection piles at Amaliahaven reached shaft resistances of at least 500 kPa in the Pleistocene sand layer (mean q_c of 45 MPa)—far in excess of the NEN 9997-1 limiting resistance of 135 kPa. However at these loads, the screw injection piles failed at the interface between the outer grout body and the permanent steel casing, suggesting that while geotechnical capacities can be mobilised far beyond the existing limiting resistances, the structural capacity of the pile can still be a limiting factor.

DESIGN FACTORS FOR SCREW DISPLACEMENT PILES

The base capacities of the screw injection piles at Amaliahaven and Delft were, on average, 43% lower than the base capacity predicted by NEN 9997-1 (where $\alpha_{p,4D/8D}$ = 0.63 for screw injection piles). No trend with installation parameters was observed with the piles' base capacities, including the advancement ratio (schraapfactor), grout flow rate or crowd force. With these installation parameters in mind, the analysis was extended from screw injection piles to all types of screw displacement piles, such as Atlas, DPA, Omega and Olivier piles. The analysis (figure 6) supported the lower α_p values measured at the InPAD test sites, showing that screw displacement piles tend to mobilise base resistances much like a soil-replacing, bored pile instead of a fully displacing, driven precast pile.

At Amaliahaven and Delft, structural failure in the screw injection piles with a permanent casing meant that both the peak and residual shaft resistances were affected by this failure . In contrast,

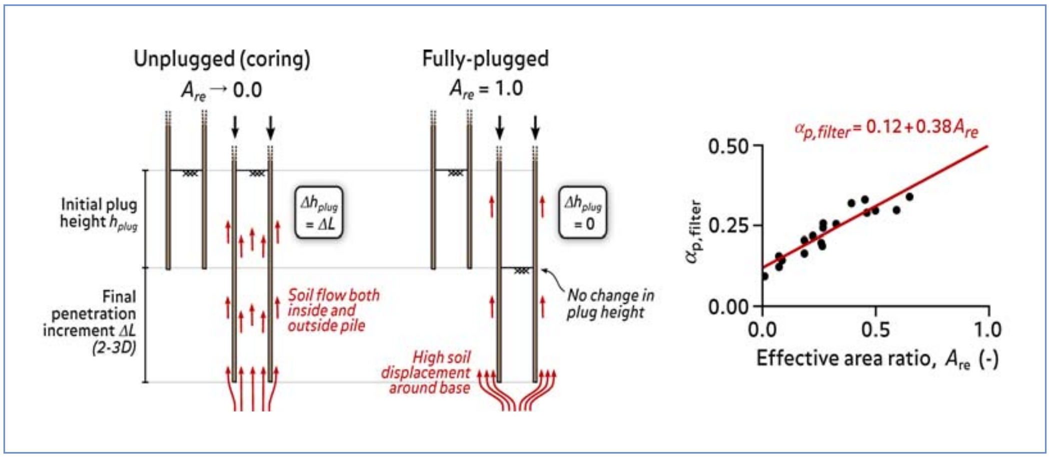

Figure 7 – Influence of plugging towards the end of installation on the pile base capacity.

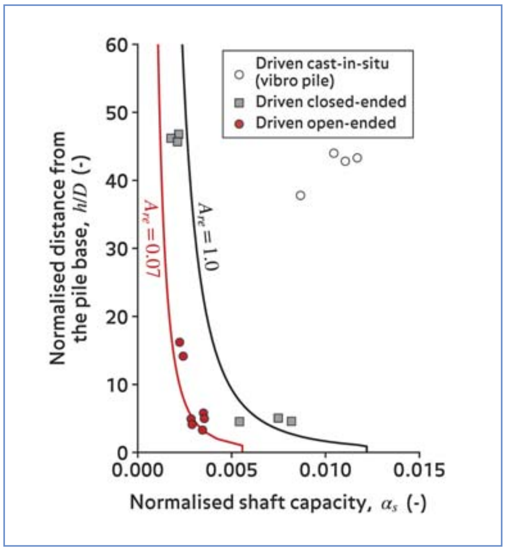

Figure 8 – Measured shaft capacities in sand compared to the Unified design method.

the screw injection piles with a reusable casing (Fundex piles) at Delft, fully mobilised their shaft capacity in the sand layer, with post-peak softening of up to 30%. Considering the peak resistances, both types of screw injection piles at Amaliahaven and Delft mobilised higher-than-expected shaft resistances in sand, with peak α_s values ranging from 0.012 to 0.018.

Instrumented database records also indicated higher α_s values than that prescribed by NEN 9997-1 ($\alpha_s = 0.009$). When combining an α_s of 0.012 with an $\alpha_{p,filter}$ of 0.24, these gave improved predictions to the total capacities of the database piles. However, variability in the results suggests that factors like pile geometry, installation procedure or concreting may still influence the shaft response of screw displacement piles. In this regard, the tests at Lemmer investigated the influence of grout injection parameters on the shaft capacity of screw injection piles. Nevertheless, no clear correlation could be found across the range of parameters considered.

BASE RESISTANCE OF OPEN-ENDED PILES

Although the 1220 mm diameter open-ended piles on the Maasvlakte remained largely coring during installation, they behaved as fully plugged under static loading. An $\alpha_{p,filter}$ equal to about 0.20 was found across the four piles, where $q_{c,filter}$ ranged from 15 to 55 MPa. Relatively small base displacements were needed to mobilise the annular base resistance, whereas a soft, almost linear mobilisation was found for the plug resistance. Internal shaft friction was only observed over a height of a couple diameters from the pile base.

The tests showed that the two extreme cases of NEN 9997-1—fully plugging during installation and fully coring during static loading—do not align with the observed behaviour of open-ended piles. The low α_p values can be explained by the fact that only the annulus contributed to soil displacement during installation. Therefore, the soil below the plug is barely pre-stressed, just like a non-displacement pile. In addition, the plug also compresses under static loading. The measured base responses were accurately predicted by the new Unified design method for driven piles (Lehane et al., 2020), which accounts for the degree of soil displacement during installation through the effective area ratio A_{re} (figure 7).

FRICTION FATIGUE

Load cycling under repeated hammer blows reduces a pile's shaft resistance — a phenomenon known as friction fatigue. In the Unified design method, friction fatigue is modelled as a function of the distance from the pile base h, divided by the pile diameter D:

$$\alpha_s \sim \left(\frac{h}{D}\right)^{-0,4} \qquad (3)$$

Figure 8 shows this relationship, where an effective area ratio A_{re} of 1.0 represents a closed-ended pile and an A_{re} of 0.07 representing the open-ended piles at Witte Zeeweg. The shaft capacities of the driven closed-ended and open-ended piles vary with distance from the pile base, in close agreement with the predictions of Equation 3. Despite the similarities in installation between driven cast-in-situ and driven precast piles, figure 8 suggests that driven cast-in-situ piles are not affected by friction fatigue. This discrepancy likely results from processes like concrete casting and casing withdrawal dominating over the mechanisms that cause friction fatigue in driven precast piles.

Recommendations for NEN 9997-1

Based on the results of field testing and physical modelling, the following recommendations have been made from the InPAD project:

- The filter method (Boulanger and DeJong, 2018) should be used to determine the design cone resistance $q_{c,avg}$ for pile base capacity formulations.
- No limiting resistances are needed up until the highest measured base and shaft resistances at the InPAD test sites (at Amaliahaven: $q_b = 30$ MPa in the driven closed-ended piles and $q_s = 600$ kPa in the screw injection piles).
- NEN9997-1 should account for the lower-than-forecasted base capacities and higher-than-forecasted shaft capacities that were measured in the screw displacement piles.
- In line with the Unified design method, the α_p factor for open-ended piles should account for the degree of soil displacement during installation.
- Friction fatigue should be considered for jacked, driven open-ended and driven closed-ended piles. In driven cast-in-situ piles, no friction fatigue was observed.

Incorporating these recommendations into design codes is ongoing. For instance, the NEN committee Geotechniek is looking at the design factors for screw displacement piles and a CROW committee has also started updating the CUR 2001-8 guideline 'Bearing capacity of steel pipe piles'. In addition, the field tests at Rotterdam have already been used for quay wall design as part of the self-declaration process of NPR 7201, demonstrating how instrumented field tests can lead to substantial cost and environmental savings (Roubos et al., 2024).

Future research

With that said, there are still areas of improvement in the understanding of pile behaviour and research is continuing at TU Delft and Deltares into each separate area. In particular, this research focusses on maximising the use of installation data and understanding how pile installation affects a pile's structural and geotechnical capacities. Other effects, like pile aging and foundation reuse, are also being considered as part of a database review and a study of long-term monitoring data from different structures.

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